DEFENCE R&D DÉFENSE

Navigation Technologies for Micro-Aerial Vehicles

F Wong
DRDC Valcartier

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Challenge Mission

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Navigation is Key

- Classical approach
  - sensors
  - algorithms
- Biomimetic approach
  - sensors
  - algorithms

Classical Approach - Sensors

Inertial Measurement Unit	
Crossbow ANC-1000 www.moog-crossbow.com Microstrain 3DM-GX3 www.microstrain.com SBG IG-500N www.sbg-systems.com 	acceleration angular rate magnetic field leads to estimation of velocity position heading

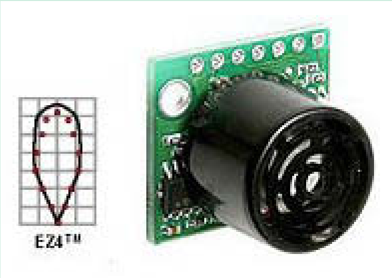
Classical Approach - Sensors

Infrared Time of Flight Scanner	
Hokuyo UTM-30LX www.hokuyo.aut.jp/02sensor Sick LMS 111 www.sick.com Velodyne HDL-32E www.velodynelidar.com 	2D range max. range : 5 m to 30 m 3D range max. range : 70 m working principle: time taken for laser pulse to travel from an illuminator to objects in the FOV and back to the detector

Classical Approach - Sensors

Infrared Time of Flight Camera	
MESA SR4000 www.mesa-imaging.ch 	3D range max. range : 5 m working principle: time taken for light to travel from an active illumination source to objects in the FOV and back to the sensor

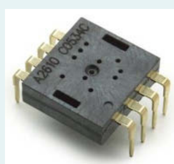
Classical Approach - Sensors

Ultrasonic Range Finder	
Devantech SRF http://www.robotshop.com/ca/sensors.html Maxbotix XL-MaxSonar www.maxbotix.com Parallax PING www.parallax.com 	1D range max. range : 2 cm to 10 m working principle: time taken for sound to travel from an active transducer to objects in the beam width and back to the detector

Classical Approach - Algorithms

Reactive Obstacle Avoidance	
Instantaneous mapping of environment and path generation.	Durham et al. (2008), IROS, 1-9 Minguez & Montano (2004), IEEE Trans Robotics and Auto., Vol. 20, 45-59 Simmons (1996), Proc IEEE Intl Conf Robotics and Auto, 3375-3382 Ulrich & Borenstein (1998), IEEE Intl Conf Robotics and Auto, 1572-1577
Simultaneous Localization and Mapping	
Incremental build of a spatially consistent map with concurrent computation of location within the map to allow path planning.	Celik et al. (2008), AIAA GNC Conf, AIAA 2008-6670 Grisetti et al. (2007), Robotics and Autonomous Syst, Vol. 55, 30-38
Structure from Motion	
Reconstruction of vehicle pose relative to the 3D environment through feature-point tracking in successive images.	Prazenica et al. (2007), AIAA GNC Conf, AIAA 2007-6830 Watkins (2007), PhD Thesis, U Florida

Biomimetic Approach - Sensors

Vision	
monocular camera	array of CCD or CMOS detectors
Centeye www.centeye.com 	compound eye composed of elementary motion detectors
optical mouse ADNS-2610 https://www.sparkfun.com/products/10105 	simple elementary motion detector
PrimeSense www.primesense.com 	3D scanner using structured light

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Hierarchy of Technologies for Vision-based Micro-Aerial Vehicles

Image extraction

Optical flow estimation

Feature extraction

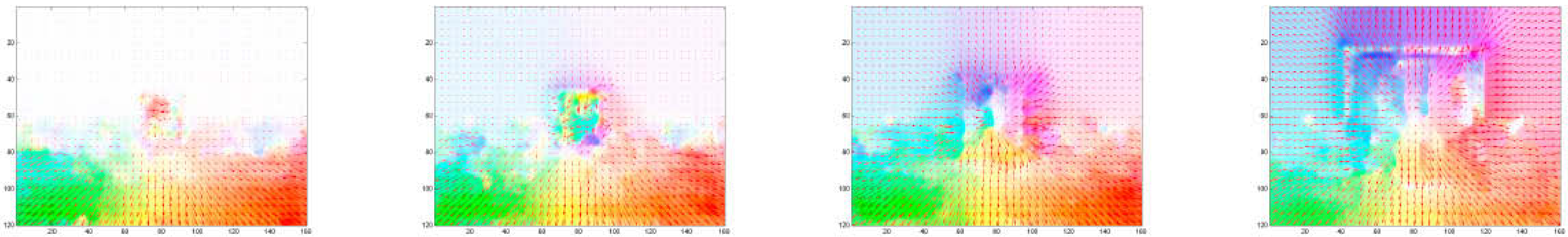
Navigation law

Vehicle control law

Actuator commands

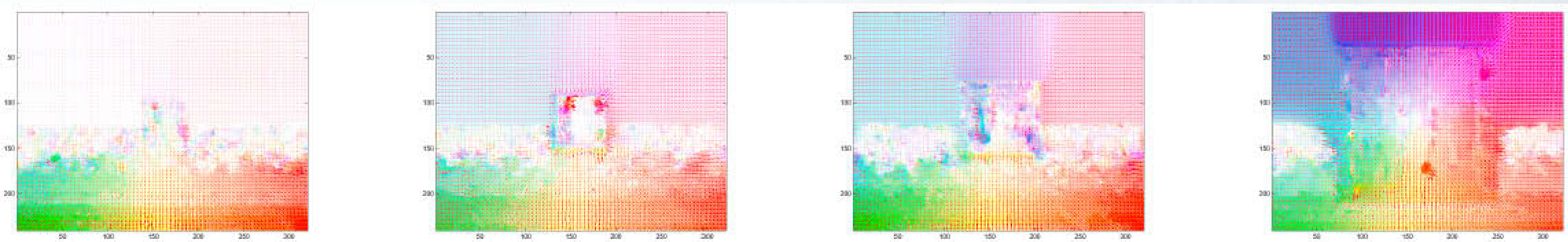
Image Extraction

- 160x120 pixels, 10 fps, computation time = 0.23 s



(a) Position # 1 (b) Position # 2 (c) Position # 3 (d) Position # 4

- 320x240 pixels, 30 fps, computation time = 2.26 s



(a) Position # 1 (b) Position # 2 (c) Position # 3 (d) Position # 4

Optical Flow Estimation

- Optical flow due to general camera motion

Coombs, D. et al. (1998), IEEE Trans Robotics and Automation, Vol. 14, 49-58.

$$u = (1/Z)(-T_x + xT_z) + [xy\omega_x - (1 + x^2)\omega_y + y\omega_z]$$
$$v = (1/Z)(-T_y + yT_z) + [(1 + y^2)\omega_x - xy\omega_y - x\omega_z]$$

- Optical flow based on image pixel brightness

$$\frac{\partial I}{\partial x} V_x + \frac{\partial I}{\partial y} V_y + \frac{\partial I}{\partial t} = 0$$

Optical Flow Estimation

- Horn & Schunck – global smoothness constraint

Horn and Schunck (1981), Artificial Intelligence, Vol. 17, 185-203.

$$E = \iint \left[(I_x u + I_y v + I_t)^2 + \propto^2 \left(\|\nabla u\|^2 + \|\nabla v\|^2 \right) \right] dxdt$$

$$dxdy$$

- Liu (Lucas & Kanada) – local smoothness constraint

Lucas and Kanade (1981), Proc. Of DARPA Image Understanding Workshop, 121-130.

Liu (2009), PhD Thesis, MIT

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} \sum_i I_x(q_i)^2 & \sum_i I_x(q_i) I_y(q_i) \\ \sum_i I_x(q_i) I_y(q_i) & \sum_i I_y(q_i)^2 \end{bmatrix}^{-1} \begin{bmatrix} -\sum_i I_x(q_i) I_t(q_i) \\ -\sum_i I_y(q_i) I_t(q_i) \end{bmatrix}$$

- Other algorithms

vision.middlebury.edu/flow/eval

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Feature Extraction – Time to Contact

- TTC based on flow divergence

Coombs, D. et al. (1998), IEEE Trans Robotics and Automation, Vol. 14, 49-58.

$$\frac{\partial u}{\partial x} = \rho T_z + y\omega_x - 2x\omega_y$$
$$\frac{\partial v}{\partial y} = \rho T_z + 2y\omega_x - x\omega_y$$

$$T_c = \frac{2}{\bigtriangledown(u,v)}$$ at (x, y) = (0,0)

- TTC at pixel location (x, y)

Low & Wyeth (2005), Australasian Conf Robotics and Automation, 1-10.

$$\mathbf{T_c} = \frac{\cos\phi \times \sin\phi}{\dot{\phi}}$$

$\dot{\phi} = u \cos \theta + v \cos \theta$
ϕ = spherical angle between optical axis and vector from focal point to pixel on image plane
θ = polar angle on image plane

Navigation Law

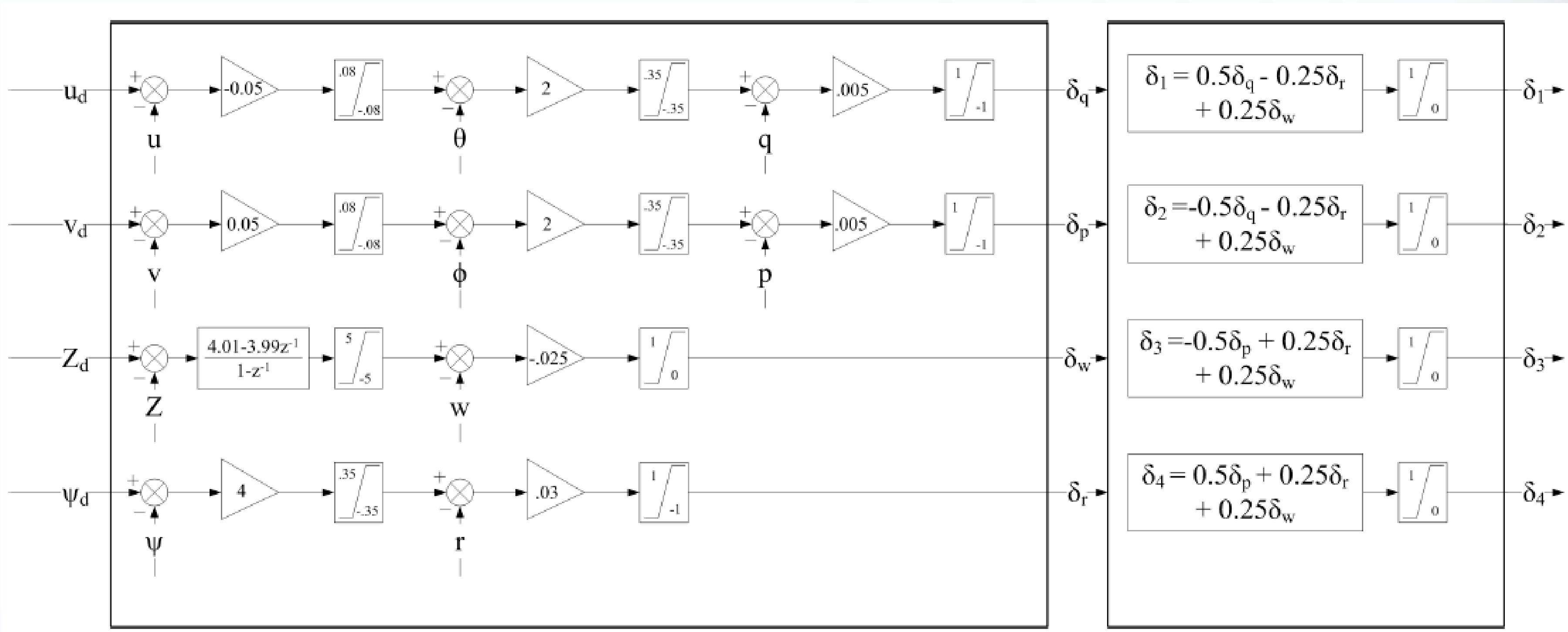
- Global TTC

$$
\begin{aligned}
T_{cbalance} &= \sum_{i=0}^{n/2}\sum_{j=0}^{m} \mathbf{T_c(i,j)} - \sum_{i=n/2}^{n}\sum_{j=0}^{m} \mathbf{T_c(i,j)} \\
T_c &= K_{scaling}\sum_{i=0}^{n}\sum_{j=0}^{m} \mathbf{T_c(i,j)}
\end{aligned}
$$

- Heading and speed commands

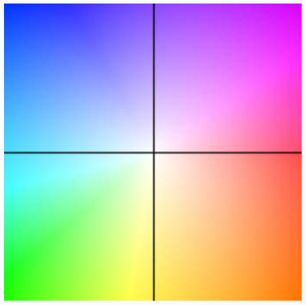
$$
\begin{aligned}
\psi_{cmd} &= (-\frac{\pi}{36} * (T_c)^2 + \frac{\pi}{4}) * sign(T_{cbalance}) \\
v_{cmd} &= (-\frac{1}{18} * (T_c)^2 + \frac{1}{2}) * sign(T_{cbalance})
\end{aligned}
$$

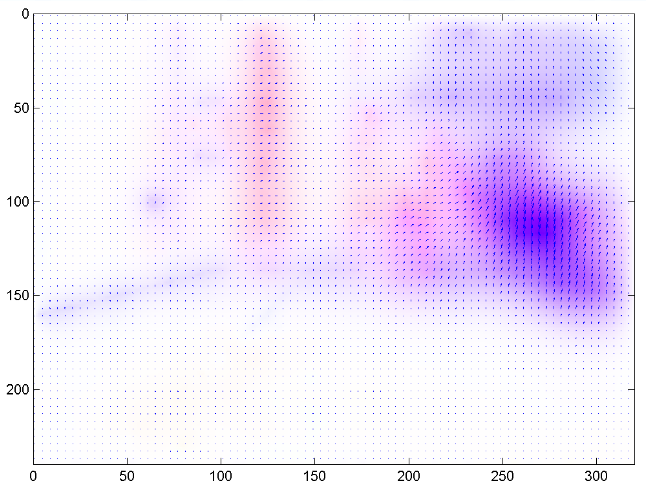
Quadrotor Control Law



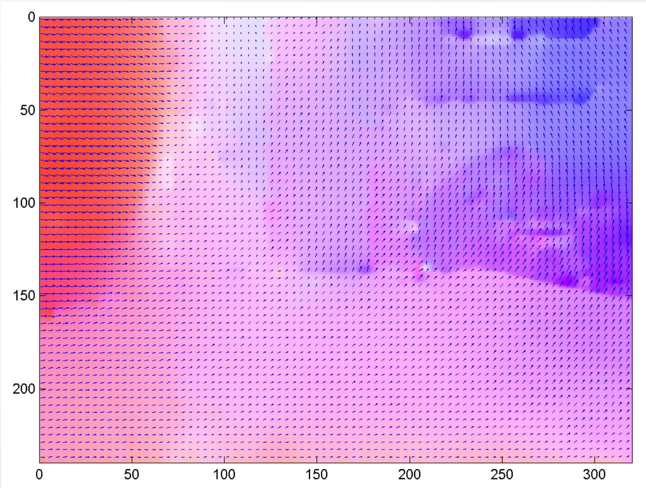
Simplified control law for simulation study only.

Comparison of Optical Flow Estimation Methods



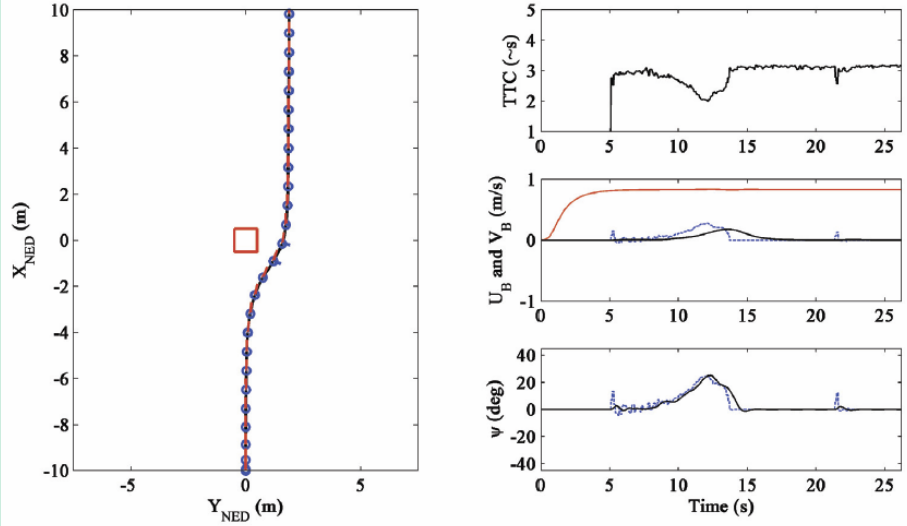
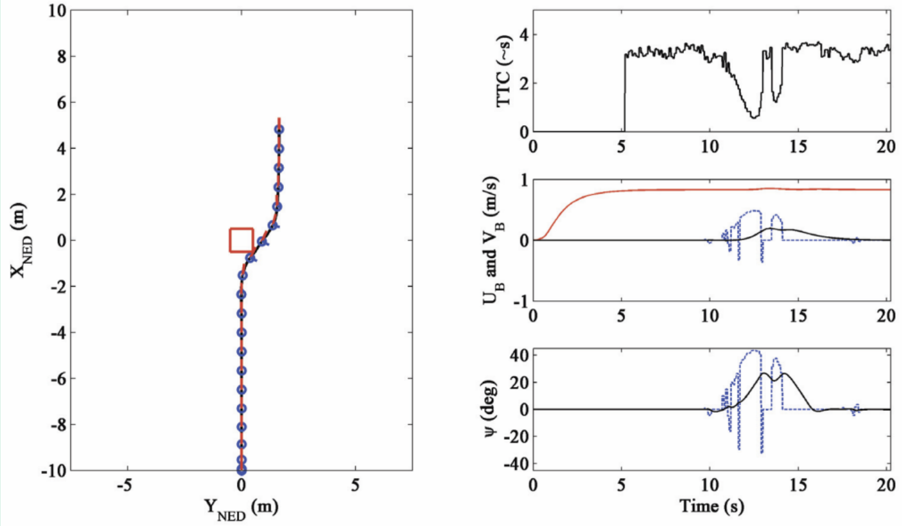


H&S

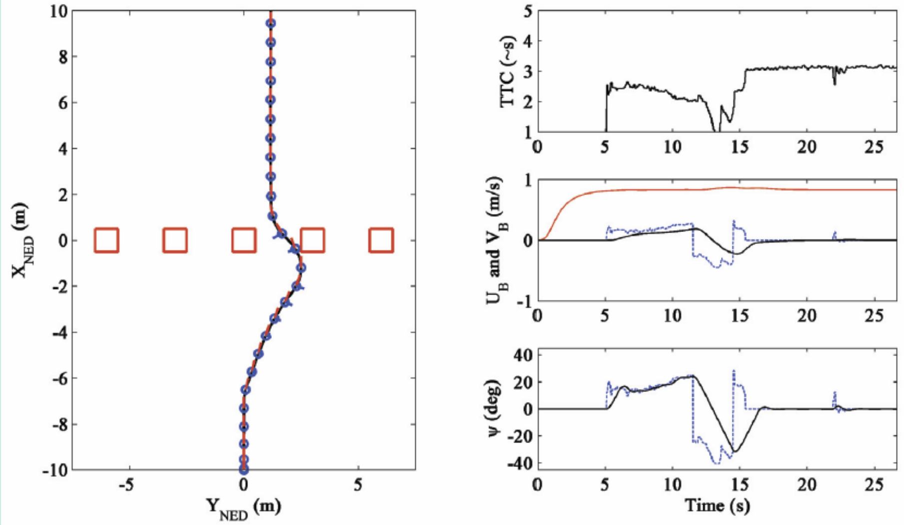
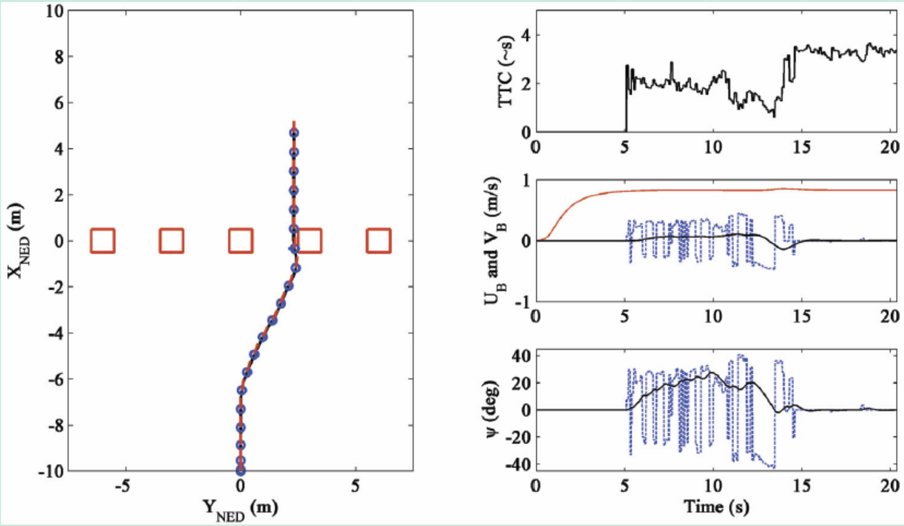


Liu

Obstacle Avoidance Simulation – 1 Obstacle

H&S optical flow	Liu optical flow
	

Obstacle Avoidance Simulation – 5 Obstacles

H&S optical flow	Liu optical flow
	

Summary

- Classical navigation approach comprised of sensors that measure distances to objects and algorithms that exploit absolute distance measurements to compute navigation commands.
- Biomimetic approach comprised of sensors that pixelate objects in an image plane and algorithms that exploit pixel movement to deduce object location in order to compute navigation commands.
- As the size of a micro-aerial vehicle reduces, the viability of using classical navigation methods decreases unless classical navigation sensors have a dramatic decrease in size, weight and power consumption.
- Vision-based navigation methods may offer an avenue to miniaturize the navigation sub-system on micro-aerial vehicles. However, further development to increase the robustness of optical flow-based navigation algorithms is required.

Other Interesting References

Ahrens (2009), "Vision-based Guidance and Control of a Hovering Vehicle in Unknown, GPS-denied Environments", Proc IEEE Intl Conf Robotics and Auto, 2643-2648.

Beyeler et al. (2007), "3D Vision-based Navigation for Indoor Flyers", IEEE Intl Conf Robotics and Auto (ICRA).

Floreano et al. (2009), Flying Insects and Robots, Springer.

Lewinger et al. (2006), "Obstacle Avoidance Behavior for Biologically-Inspired Mobile Robot using Binaural Ultrasonic Sensors", IEEE/RSJ Intl Conf on Intell Robots and Syst, 5769-5774.

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